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An experiment with approximate reasoning in site selection using 'InfraPlanner'

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Abstract

This paper discusses an application of an intelligent information system for decision-makers involved in multiple criteria group site selection problems under uncertainty. The fuzzy algorithm behind the system was developed by the authors for use in large-scale infrastructure site selection, and is validated here using a site selection problem at Brisbane Airport. The 'InfraPlanner' Spatial Decision Support System (SDSS) was created by customising ArcView GIS, and operates on raster data files. The tightly coupled system features linguistic interaction, multiple decision-maker input, uncertainty assessment, and a linguistically controllable aggregation function capable of a variety of compensatory and non-compensatory outcomes. Feedback from decision-makers involved in the experiment indicated a high level of satisfaction with outputs from the system, whilst noting some areas for future development.

1. Introduction

Site selection for facilities such as airports, highways, and heavy industry is often extremely complex. As multiple stakeholders are usually involved in the selection of a given location, there is a strategic need to take into account multiple criteria, which are often conflicting, incommensurate and subject to uncertainty. Also, the spatial variation of suitability and the weighting of each criterion is often hard to measure, and may be the basis of disagreement amongst a group of heterogeneous decision-makers. Such problems are often described as 'surprisingly difficult' [1]

The use of Geographical Information Systems (GIS) in site selection has a long history, with most approaches being based on a multiple criteria evaluation (MCE) framework. There has been much literature on MCE embedded in GIS [2-4], however most GIS-based MCE methods have inherent difficulties and limitations. Embedded MCE approaches generally assume consensus among decision-makers [5] and have little capacity for dealing with conflicts between affected parties, thereby losing potentially important information in the aggregation phase. Many authors have also noted that there is a need for accuracy measures to be incorporated into spatial datasets upon which decisions are to be made [6-8], however the nature of data uncertainty is not always easily fitted to a probability distribution, and measures of accuracy may themselves be hard to quantify. Perhaps most importantly, the use of MCE in computer-based decision support systems is limited by the fact that highly capable analytical systems are often used as simple visualization tools, primarily due to difficulties in use and understanding of the systems by strategic decision-makers [9].

'InfraPlanner' is a SDSS, developed using a fuzzy algorithm to mitigate these difficulties. Specifics of the algorithm are given in [10]. Broadly speaking InfraPlanner is an intelligent information system based on approximate reasoning that offers the following capabilities:

- Linguistic interaction: *Linguistic interaction is provided using primary term sets semantically defined by parameter-based fuzzy numbers, which may be enhanced via a hedging procedure to add more terms. Both input and feedback is accomplished linguistically.*
- Multiple decision-maker capability: *The system accepts linguistic inputs from each party involved in the decision-making process. Conflict between parties is assessed based on differing suitability and weighting judgments and factored into overall site suitability.*
- Uncertainty assessment: *There are two types of uncertainty inherent in decision-maker suitability assessments: linguistic and quantitative. Linguistic uncertainty is represented by the fuzziness of the primary suitability term, whereas quantitative uncertainty is represented using the concept of a type-2 fuzzy set and its footprint of uncertainty (FOU)* [11]. *Quantitative uncertainty is the term used here to represent uncertainty in the source data and/or its relationship with site suitability.*
- User controllable aggregation: *Users have the ability to choose an aggregation that minimizes uncertainty, risk or conflict, or maximizes compensatory suitability. A variety of compensatory and non-compensatory linguistically defined outcomes may be delivered.*
- Real-time interaction: *In raster GIS the decision area may contain millions of cells, with each cell representing an alternative that will ideally be analyzed in a real-time interactive environment. The computationally efficient fuzzy algorithm of InfraPlanner utilizes a scoring function when dealing with fuzzy quantities that minimizes calculation time and makes real-time interaction possible.*

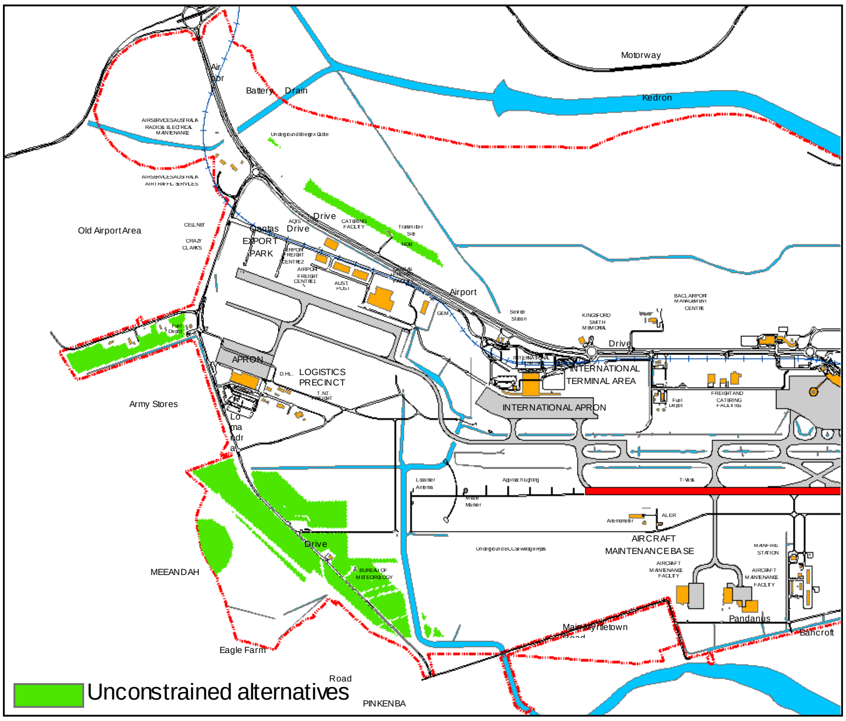

Figure 1. Unconstrained alternatives

This paper follows from existing work in development of the algorithm by discussing its application to a real world site selection task at Brisbane Airport, Australia. The remainder of the paper is structured as follows: Section 2 provides an overview of the site selection problem used in the experiment: Section 3 details input from decision-makers: Section 4 covers exploration of alternatives, Section 5 is a discussion of the outcomes of the experiment and Section 6 draws conclusions.

2. The problem

The problem worked through here concerns the location of a new construction and demolition (C&D) facility, at Brisbane Airport, Australia. The Airport occupies 2700ha of land, located 13km north east of the Brisbane CBD, adjoining Moreton bay. The site is flat and low lying, occupying part of the original Brisbane river delta, which has undergone extensive changes since the 1830s, with most of the original network of tidal waterways being replaced with constructed drains. Much of the vegetation on the site has been planted in the last 15 years, and was chosen to reduce the attraction of birds. There are, however, some environmentally sensitive areas to consider when locating new developments, as well as issues associated with airport facilities, Government legislation and the effects of airport operations on local communities.

A Construction and Demolition facility inputs masonry from demolished buildings and, via crushing and grinding, turns out various grades of landfill material. The main impacts of such an operation on its immediate vicinity are noise and dust emissions. The Brisbane Airport Corporation (BAC) is considering leasing a parcel of land on its site to a C&D facility operator primarily because of the flow on benefit of easily accessible fill material for other development sites on the Airport grounds.

Three separate groups are to be engaged in the decision-making process: The Brisbane Airport Corporation, The Commonwealth Government, and the Pinkenba residential community. The three groups differ considerably in their priorities and suitability assessments, creating a rich decision-making environment.

3. Decision-maker input

Data input primarily consists of the creation of a set of maps detailing the suitability and uncertainty assessments of each group. The first step in the process is the definition of constraints (Boolean criteria) that serve to limit the number of alternatives under consideration. After an initial consultation with decision-makers, a set of five constraints emerged:

1. Airport Boundary: The site must lie within the airport boundary
2. Existing Buildings: Sites already occupied are excluded
3. Road access: The site must be within 200m of selected access roads.
4. Zoning: The site must lay in a zone designated ‘General Industry’ or ‘Light Industry’ as defined by the BAC 1998 Master Plan.

5. Conservation: The site must not occupy an area of high conservation value.

The map of unconstrained alternatives is derived using standard GIS Boolean overlay functionality and is shown in Figure 1.

The next step in the process involves the definition and linguistic assessment of criteria that vary on a suitability scale from ‘Totally Unsuitable’ to ‘Perfect’. These criteria (referred to as factors) are represented as a set of suitability maps, created using specially designed interfaces that convert linguistic inputs from each decision-maker to a spatially explicit format as shown in Figure 2 and 3. To illustrate how the linguistic input is structured factor definition from BAC is provided below:

1. Environmental value is ‘important’: It is ‘moderately certain’ that sites of moderate conservation value are ‘good’ whilst it is ‘very certain’ that all others are ‘perfect’.
2. Zoning is ‘very important’: It is ‘very certain’ that general industry zones are ‘perfect’ whilst it is ‘moderately certain’ that light industry zones are ‘good’.
3. Tenant Amenity is ‘important’: It is ‘very certain’ that sites less than 50m from sensitive tenants are ‘totally unsuitable’. It is ‘moderately certain’ that sites 100m from sensitive tenants are ‘good’. It is ‘certain’ that sites 500m from sensitive tenants are ‘perfect’.
4. Community Impact is ‘important’: It is ‘very certain’ that sites less than 500m from Pinkenba are ‘totally unsuitable’. It is ‘uncertain’ that sites 1000m from Pinkenba are ‘good’. It is ‘very uncertain’ that sites 2000m from Pinkenba are ‘perfect’, and ‘certain’ that sites 4000m from Pinkenba are ‘perfect’.
5. Proximity to BAC Landfill Requirement is ‘moderately important’: It is ‘very certain’ that sites on Lomandra Dr are ‘perfect’. It is ‘moderately certain’ that sites on Randle Rd, Sugarmill Rd and Viola Pl are ‘good’. It is ‘moderately certain’ that sites on Airport Dr are ‘indifferent’.
6. Traffic impact is ‘important’: It is ‘very certain’ that sites on Airport Drive are ‘bad’. It is ‘moderately certain’ that sites on Lomandra Drive and Viola Pl are ‘good’. It is ‘certain’ that sites on Randle Road and Sugarmill Rd are ‘perfect’.

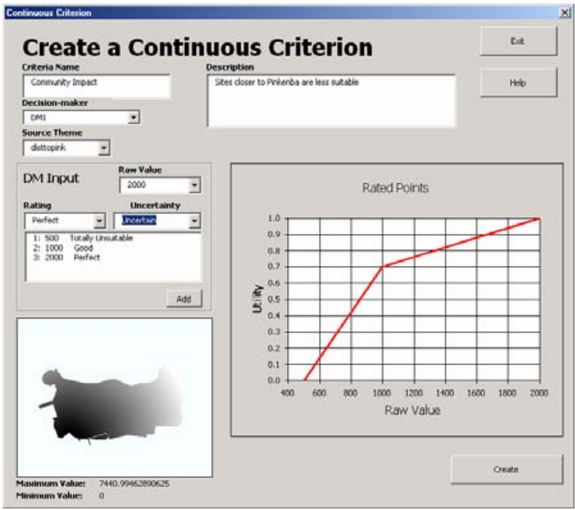

Figure 2: Creating a suitability map from a continuous variable (the charted utility function is a guide only as values are fuzzified)

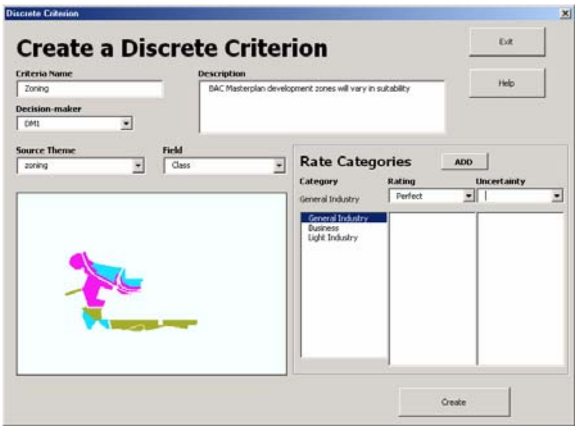

Figure 3: Creating a suitability map from a discrete (categorical) variable

InfraPlanner takes the linguistic assessments and generates raster maps, where each raster cell has a fuzzy number representative of the suitability and uncertainty assessment for each criterion from each decision-maker. Figure 4 illustrates the type-2 fuzzy concept used to accomplish this. When all maps are generated a fuzzy aggregation is performed, enabling decision-makers to interactively explore alternatives as discussed in the next section.

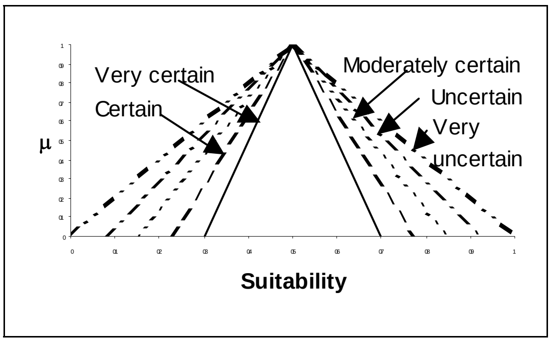

Figure 4. The effect of uncertainty assessments on the primary MF of ‘indifferent’

4. Alternative exploration

The initial aggregation provides four linguistic parameters for each alternative cell: Compensatory suitability, uncertainty, risk, and conflict. Compensatory suitability is derived from a fuzzy weighted combination of individual criterion outcomes, importance values and a relevance value representing the ability of each decision-maker to assess each criterion, as shown in Equation 1.

$$S_i = \sum_{j=1}^{J} \sum_{k=1}^{K} O_{ijk} \times R_{jk} \times W_{jk} \mid \quad i = 1 \ldots I \quad (1)$$

Where:

S_i is the suitability of alternative i.

O_{ijk} is the criteria outcome for alternative i with relation to criterion j and decision-maker k, including quantitative uncertainty.

R_{jk} is the relevance of decision-maker k's opinion with respect to criterion j.

W_{jk} is the weight assigned to criterion j by decision-maker k

Uncertainty is derived from the support of the triangular fuzzy number, as this will vary with the individual uncertainty assessments via a Type 2 scaling procedure. Risk is a measure of how each criterion outcome compares to a specified minimum, and conflict is a measure of disagreement amongst decision-makers, as shown in Equation 2.

$$R_c(i) = \frac{\overset{J}{\underset{j=1}{\vee}} \left(\overset{K}{\underset{k=1}{\vee}} (R_s(O_{ijk}) - w_{jk}) - \overset{K}{\underset{k=1}{\wedge}} (R_s(O_{ijk}) - w_{jk}) \right)}{2} \quad (2)$$

Where:

$R_c(i)$ is the conflict score for alternative i

$R_s(i)$ is the suitability score for alternative i

$\wedge$ is the minimum operator

$\vee$ is the maximum operator

Decision-makers can now decide which parameters are most important as they explore and reduce the set of feasible alternatives in an interactive, point and click environment as shown in Figures 5a and 5b. Alternatives are gradually reduced by selecting minimum standards for each of the four parameters or creating an overall adjusted suitability value by combining them as shown in Equation 3.

$$A(i) = \frac{R_s(i)w_s + (1 - R_u(i))w_u + (1 - R_r(i))w_r + (1 - R_c(i))w_c}{w_s + w_u + w_r + w_c} \quad (3)$$

Where:

$A(i)$ is the adjusted suitability value of alternative i

$R_r(i)$ is the risk score for alternative i

$R_u(i)$ is the uncertainty score for alternative i

w_s is the weighting of the suitability score

w_u is the weighting of the uncertainty score

w_r is the weighting of the risk score

w_c is the weighting of the conflict score

The adjusted suitability score is then used to generate an adjusted linguistic suitability rating. Weighting of the four parameters is via consensus, or a non-weighted averaging of each decision-maker's preferences, which enables a variety of non-compensatory outcomes to be generated.

As expected the system easily identified the preferred sites for each decision-maker individually. The three sites varied in location, and thus contained high levels of conflict. The best compensatory solution was acceptable to only two of the parties, and performing a second aggregation to minimise conflict found a slightly different solution that the third party also rejected. It was quickly ascertained that disagreement was primarily due to the third decision-maker placing primary importance on satisfying a single criterion. Unfortunately this left no locations available that were completely satisfactory to all, and the primary benefit gained in from the system was the clear identification of the source of conflict, which has become the subject of negotiation between parties.

5. Discussion

The nature of the site selection problem presented here is typical of many real world situations. A fundamental problem in designing systems to solve such problems is that there is often no universally accepted solution to find, and it is not always possible to derive the best compromise from initial assessments. Most GIS based decision-making methods assume that crisp numerical suitability assessments can be processed according to a pre-determined algorithm to derive a solution. However the complex nature of many site selection decisions make such assumptions unrealistic. It was noted during the experiment that decision-makers were reluctant to place their faith in a derived solution without fully understanding how that solution was obtained. This creates a significant hurdle for system designers whose aim is to replicate, and by default replace, the decision-making process. Using a pre-determined optimization algorithm is standard procedure in many areas of problem solving, and works particularly well when the exact utility of a solution can be precisely measured and used as feedback to improve performance. However the exact utility of a solution in site selection is seldom known. Multiple, conflicting criteria, and the added human element of conflicting opinions of measurement and importance create an ill-structured problem that is often dynamic, in that assessments may change as the solution space is examined. It is also relevant to note that problem-solving strategies vary from person to person, making the group situation a particularly dynamic environment.

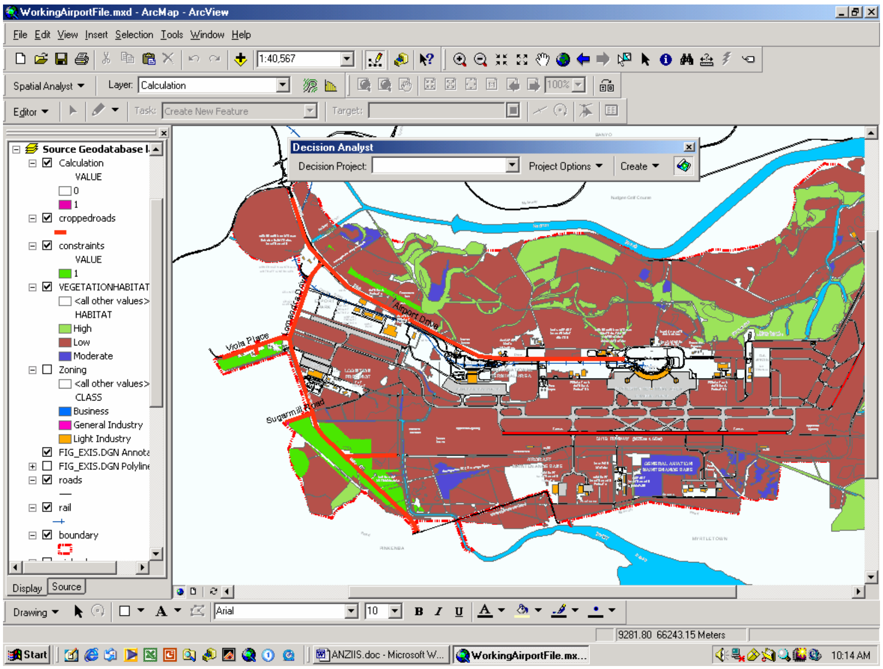

Figure 5a: Choosing alternatives

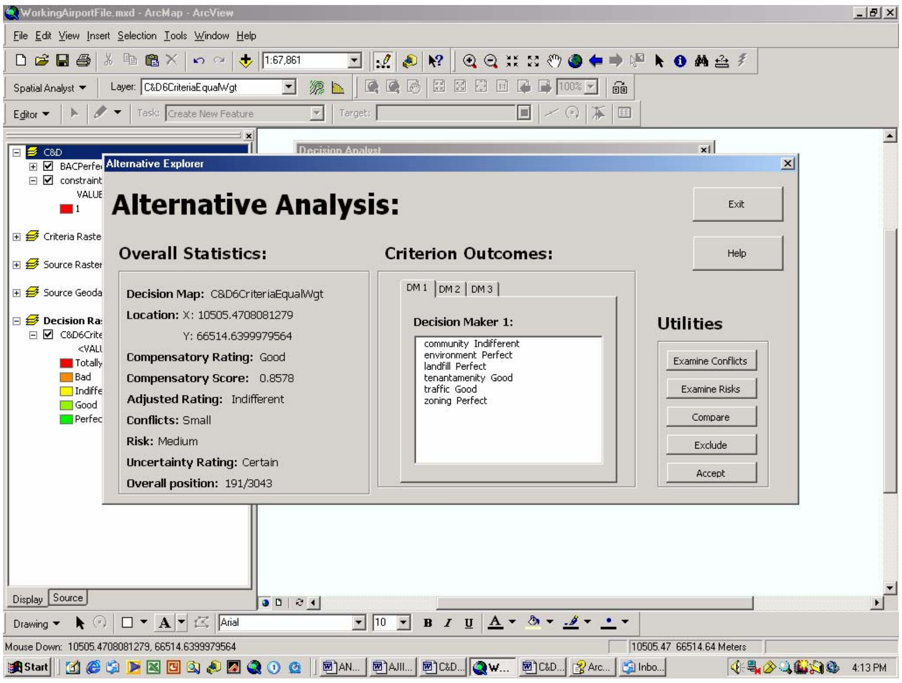

Figure 5b: Alternative exploration and feedback

InfraPlanner was designed as an intelligent information system to provide decision-makers with relevant, understandable processed information, whilst leaving them in control of the decision-making process. To this end it was noted that decision-makers expressed a high level of satisfaction with outputs, as they enabled the group to find the core elements behind their conflicting assessments. In a real world situation, where political issues can dominate operational concerns, it is often most beneficial to identify these core areas as they may be traded off for concessions outside the sphere of the site selection task. Outcomes from the experiment discussed in this paper confirm this point of view.

Giving decision-makers the ability to generate a variety of solutions that maximized aggregated suitability or minimized risk, conflict and uncertainty provided an easily understandable way for decision-makers to take more control of the analysis, rather than accepting imposed heuristics. Moreover, whilst the system makes computationally deriving a solution from input data possible, it’s major strength was the high information value of outputs. The experiment confirmed that a focus on a meaningful, interactive exploration of alternative outcomes is a valid way to support decision-makers in their task.

The experiment also confirmed some important limitations of the system: Firstly, the method used is limited to analyzing problems with a single objective, which makes it unsuitable for situations where multiple facilities are to be located simultaneously or multiple land uses considered. Secondly, the use of single cells as alternatives does not accurately represent the true size and spatial configuration of a proposed development, which has been surprisingly seldom noted [12]. Lastly, utilizing linguistic terms for data input may unnecessarily limit the accuracy of results in those cases where hard quantitative data is available.

Another difficulty noted in the group experiment was the requirement to define discrete criteria. As an example, some decision-makers noted overlap in their perception of community impact versus environmental impact. Some authors have described multicriteria decisions, particularly those with multiple objectives, in terms of a hierarchical structure, whereby some criteria encompass others, eg [13]. In a group situation this provides another area for disagreement and/or misunderstanding.

6. Conclusions

The experiment confirmed the validity of an approximate reasoning approach to group site selection problems under uncertainty. The InfraPlanner system enabled decision-makers to express their assessments linguistically and receive meaningful linguistic feedback, whilst taking more control of the process than other methods allow, and a high level of satisfaction with outputs was expressed.

The results indicated a definite benefit from utilizing a multi-decision-maker framework, as the identification of conflicts between parties could be easily accomplished. An emphasis on providing meaningful processed information, rather than offering a heuristically derived solution was also found to be beneficial.

Further work is needed to design site selection algorithms that are capable of handling multiple facility problems, and explicitly include the size and spatial configuration of the required land parcels. Genetic algorithms offer a promising method to explore feasible alternatives without resorting to the massive number of calculations required to fully examine the solution space of such problems.

Acknowledgements

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